ECE 371
Materials and Devices

10/22/19 - Lecture 16

Drift Current, Mobility, Conductivity/Resistivity, Velocity Saturation

General Information

- Homework 4 solutions posted
- Homework 5 assigned and due 10/24
- Midterm #2 on 10/31, covers Ch. 3, 4, 5
- Example problems from previous midterms posted
- Reading: 5.2-5.3

Carrier Transport

- We now know the carrier densities n_0 and p_0 (Ch. 4)
- Next: Determine processes by which electrons and holes move in the semiconductor
- ***Drift:*** movement of carriers due to electric fields
- ***Diffusion:*** movement of carriers due to concentration gradients

Drift Current Density

- Net movement of charges due to an electric field gives rise to a drift current: $J_{drf} = \rho v_d$, where ρ is the volume charge density and v_d is the average drift velocity
- For holes, $\rho = ep$, where e is the magnitude of the electronic charge and p is the hole concentration
- Holes will accelerate, experience a collision with an ionized impurity or thermally vibrating lattice atom, and then begin accelerating again
- Introduce concept of ***mobility*** – describes how well a particle will move in a crystal under an applied electric field
- The average drift velocity for holes is proportional to the mobility and the electric field, $v_{dp} = \mu_p E$, so the drift current for holes is $J_{p|drf} = e\mu_p pE$
- The total drift current including electrons is given by $J_{drf} = e(\mu_n n + \mu_p p)E$
- Both drift currents are in the same direction as the electric field

*see in-class notes

Mobility Effects

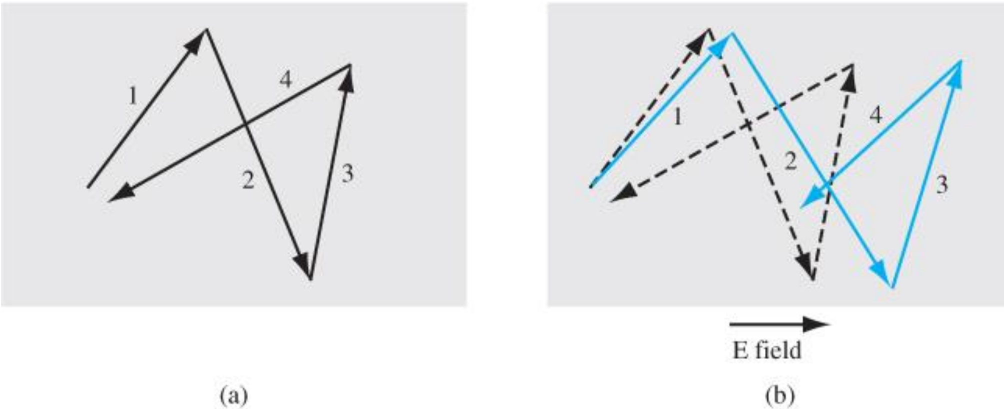


Figure 5.1 | Typical random behavior of a hole in a semiconductor (a) without an electric field and (b) with an electric field.

carrier mobility

$$\mu_n = \frac{e\tau_{cn}}{m^*_{cn}}$$

$$\mu_p = \frac{e\tau_{cp}}{m^*_{cp}}$$

τ_c = mean time between collisions
m^*_c is the conductivity effective mass (see App. F)

$$\frac{1}{\mu} = \frac{1}{\mu_I} + \frac{1}{\mu_L}$$

Two scattering mechanisms are dominant in semiconductors:

1. Phonon (lattice) scattering – due to thermal vibrations, $\mu_L \propto T^{-3/2}$
2. Ionized Impurity scattering – due to Coulomb interaction with ionized impurities, $\mu_I \propto T^{3/2}/N_I$

Mobility vs. Temperature

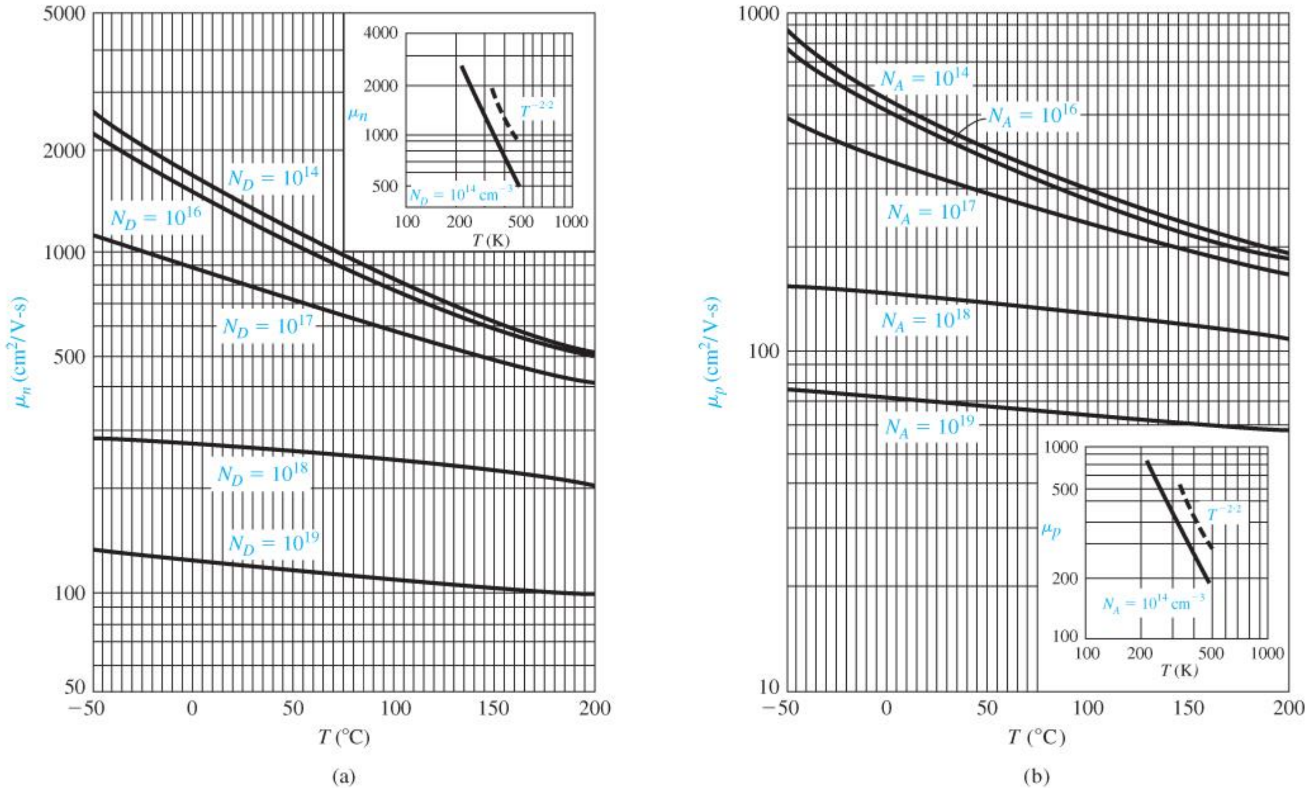


Figure 5.2 | (a) Electron and (b) hole mobilities in silicon versus temperature for various doping concentrations. Inserts show temperature dependence for "almost" intrinsic silicon.
(From Pierret [8].)

Mobility vs. Impurity Concentration

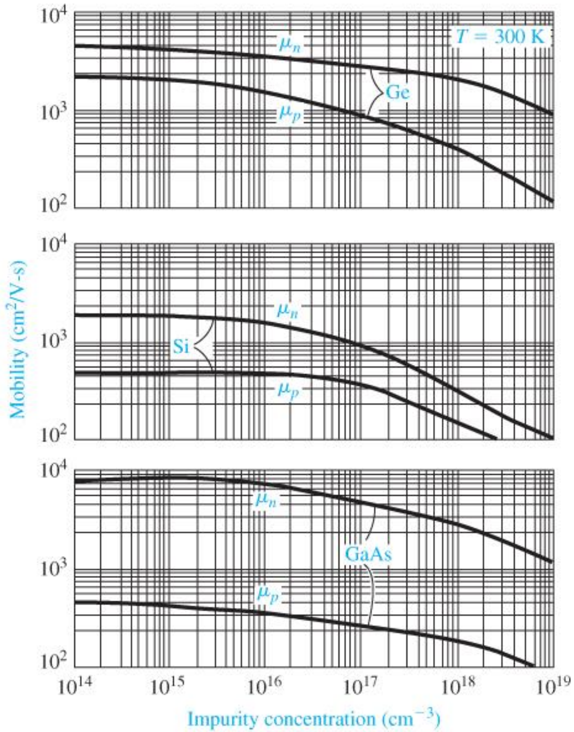


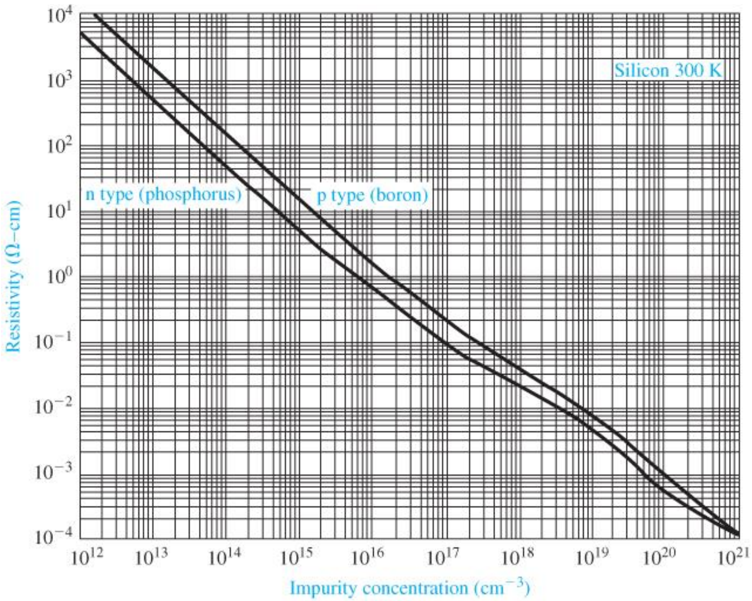
Figure 5.3 | Electron and hole mobilities versus impurity concentrations for germanium, silicon, and gallium arsenide at $T = 300$ K.
(From Sze [14].)

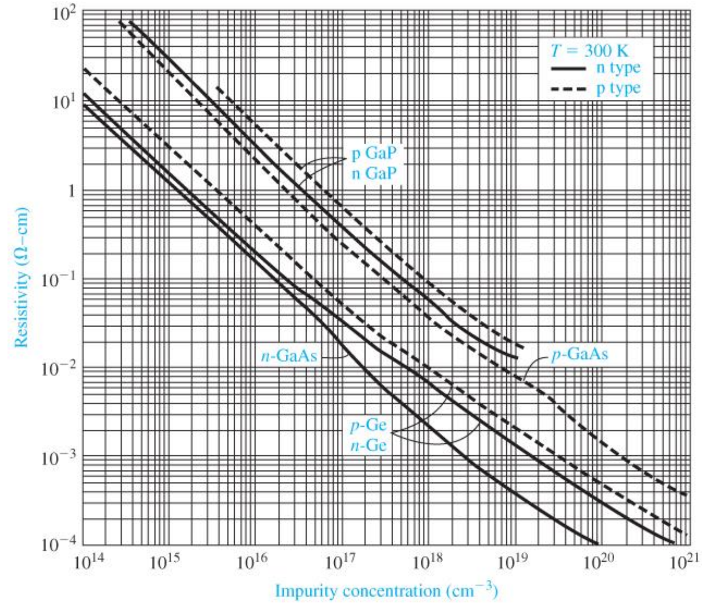
Table 5.1 | Typical mobility values at $T = 300$ K and low doping concentrations

	μ_n (cm²/V-s)	μ_p (cm²/V-s)
Silicon	1350	480
Gallium arsenide	8500	400
Germanium	3900	1900

- Higher impurity concentration implies higher probability of collision
- At higher temperatures, impurity scattering goes down
- Undoped silicon dominated by phonon (lattice) scattering

Resistivity (ρ)





$$\boxed{\rho = \frac{1}{\sigma} = \frac{1}{e(\mu_n n + \mu_p p)}}$$

- σ is the conductivity
- Function of mobility and carrier concentration
- Controllable with doping
- p-type resistivity is usually higher than n-type resistivity

Relation of Resistivity to Resistance

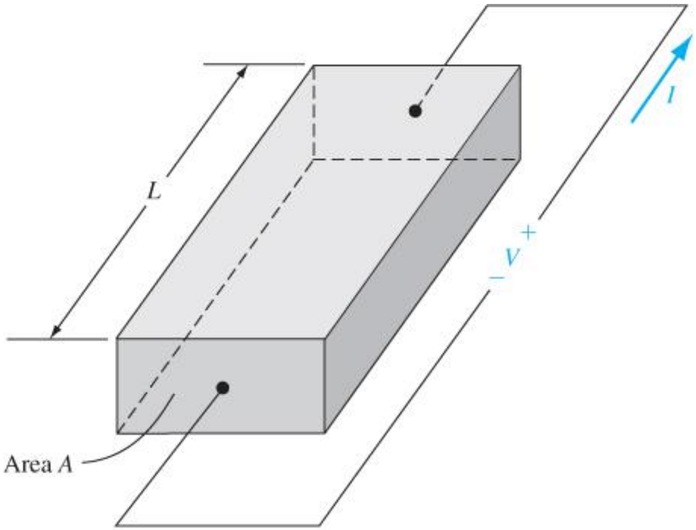


Figure 5.5 | Bar of semiconductor material as a resistor.

$$\boxed{R = \frac{\rho L}{A}}$$

- Current density: $J = I/A$
- A is the cross-sectional area
- L is the length
- Resistivity is a material property
- Resistance is dependent upon geometry

n_0 and σ vs. Temperature

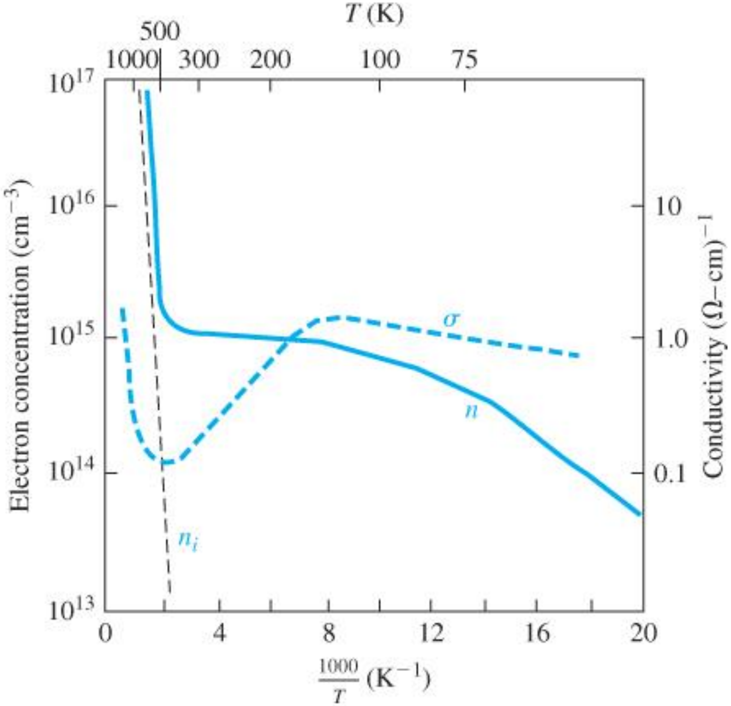


Figure 5.6 | Electron concentration and conductivity versus inverse temperature for silicon.
(After Sze [14].)

- At high T, n_i increases and dominates n_0 and σ
- Around room temperature, n_0 is almost constant (complete ionization) but σ decreases with increasing T since μ_n decreases
- At low T, freeze out begins and n_0 and σ decrease

Exercise Problems

EXERCISE PROBLEM

Ex 5.3 A compensated p-type silicon material at $T = 300$ K has impurity doping concentrations of $N_a = 2.8 \times 10^{17}$ cm^{-3} and $N_d = 8 \times 10^{16}$ cm^{-3}. Determine the (*a*) hole mobility, (*b*) conductivity, and (*c*) resistivity.

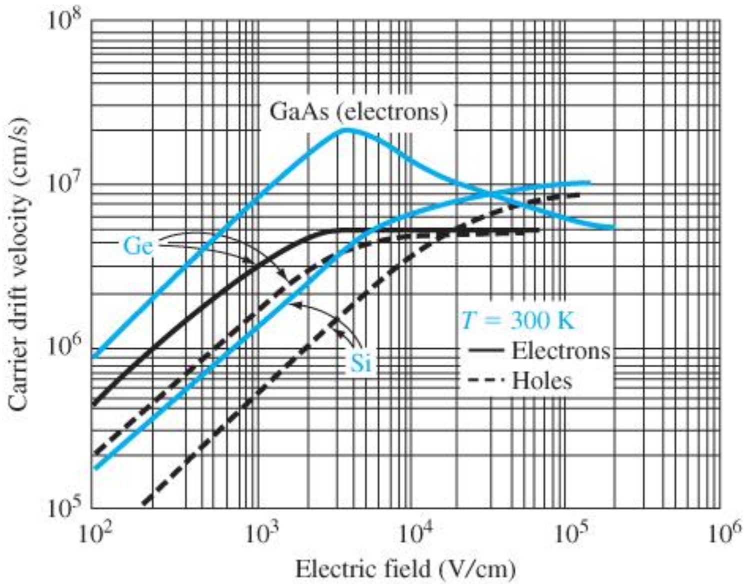
[Ans. (*a*) $\mu_p \cong 200$ cm^2/V-s; (*b*) $\sigma = 6.4$ $(\Omega\text{-cm})^{-1}$; (*c*) $\rho = 0.156$ $(\Omega\text{-cm})$]

EXERCISE PROBLEM

Ex 5.4 A bar of p-type silicon, such as shown in Figure 5.5, has a cross-sectional area $A = 10^{-6}$ cm^2 and a length $L = 1.2 \times 10^{-3}$ cm. For an applied voltage of 5 V, a current of 2 mA is required. What is the required (*a*) resistance, (*b*) resistivity, and (*c*) impurity doping concentration? (*d*) What is the resulting hole mobility?

[Ans. (*a*) 2.5 kΩ; (*b*) 2.083 $(\Omega\text{-cm})$; (*c*) $N_a \cong 7.3 \times 10^{15}$ cm^{-3}; (*d*) $\mu_p \cong 410$ cm^2/V-s]

Velocity Saturation



Materials	v_s (cm/s)
Si	1.0e7
GaAs	7.2e6
SiC	2.2e7
GaN	2.5e7

- Saturation velocity is the maximum velocity a carrier can attain in the semiconductor
- Determines the ultimate "speed limit" or frequency limit of transistors
- Mobility is a function of electric field at high field strengths
- When v_d saturates, so does J_{drf}
- Saturation caused by interaction with phonons